THE ANIMAL AS A MACHINE.

BY ROBERT H. THURSTON, DIRECTOR OF SIBLEY COLLEGE, CORNELL UNIVERSITY.

THE vital system, in spite of the study bestowed upon it from the days of Plato and of Aristotle, and by the most acute of modern men of science, remains to-day the most mysterious of all the wonders of creation. It embodies the representative energies of all the realms of nature. The chemist, the physicist, the engineer, the biologist, the sociologist, the student of mental philosophy, and the moralist,—all thinkers and investigators in all departments of science—find here problems as yet absolutely defying solution, enigmas of sphinx-like obscurity and of infinitely more than sphinx-like antiquity. They stand perpetually before us, challenging and tantalizing us by their familiar externals, by their always mysterious internal operations. All that we really know is that every animal, human or other, from the greatest of scientific men or the most famous statesman down to the most insignificant worm or almost protoplasmic organism, is a machine of marvellous intricacy and astonishing perfection; self-perpetuating; self-repairing; capable of performing tasks of the utmost difficulty as a "prime motor," and as a vehicle for the contained and directing soul; automatic in its essential internal movements; competent to conduct all those unseen and mysterious operations often for years, for decades, sometimes for a century and more, without the slightest knowledge on the part of the imprisoned mind, of their character, of their method or of their mutual relations.

The mind of the individual thus confined in the organism, however lofty and intelligent, is usually unaware, by any sensation, whether these internal transfers and transformations of energy are going on at all or not, and, as a rule, the more perfect

their action, the less the consciousness of their operation. In most cases, the very existence of an organ is unknown to the possessor until its action is, by some derangement, rendered imperfect. Physical, chemical, vital, and intellectual forces and powers are all utilized and illustrated in the movements and accomplishments of this miracle among miracles; and the mind resident in the very midst of its marvels, after unnumbered centuries and millenniums, has learned almost nothing of the modes of action of any one of its internal energies. It even still puzzles itself with the question: Is the vital machine thermo-dynamic, thermo-electric, chemico-dynamic, chemico-electric, or a linked chain of chemical, physical, and dynamic powers, united with vital energies having as yet undiscovered characteristics?

There is little, if any, doubt that there exist in the vital organism forces and energies which scientific research has not yet touched; but it may be that, aside from the initial vital powers and those of the soul and the intellect, the animal machine may illustrate simply the transformation of only well-known forms of energy through processes wholly or in part unfamiliar. But, whatever may be the fact in this regard, it may probably be safely asserted that in this machine, as in any and every other, "nothing is produced from nothing," and every manifestation of energy comes of the transfer or transformation of some antecedent energy of equivalent amount. Whatever the outgo of the system, there must be an equivalent income of energy in that or other and transformable kind. This is the first of the laws of the science of "energetics," a science which underlies every phenomenon in the organic world and every department of nature in which motion occurs. It is a fundamental law to which no exceptions are known and to which no exceptions are believed to exist. But it is supposed—though by no means proven or certain—that we know just what enters this "prime mover" and vital machine, and as exactly what is rejected from it or produced by it.

This is certainly true, so far as the familiar forms of matter and force are concerned. What as yet unknown forms of matter and what still undiscovered forces and energies affect it or are affected by it, no one can say. Possibly there may be none; very possibly there may be many. We certainly do not yet know what are the exact compositions of some of the organic compounds pro-

duced in the body for special uses, as, for example, the fatty substances of low-temperature combustion which are employed by the fire-fly and glow-worm in the production of light without heat, or the unstable composition of nerve-cells and of the gymnotus' voltaic battery. We have no positive clue to the nature of that mysterious force which flexes the muscles, bends a finger, moves a limb, or keeps the whole automatic system in operation for threescore years and ten, still less of the method of telegraphy which directs it or of the even more mysterious mental and intellectual forces and powers back of all and hidden in the most inaccessible recesses of the complicated mechanism within which we "live and move and have our being."

The anatomical structure of this singular machine is well understood, and the surgeon can do wonderful work in its dissection, its repair and reconstruction; but of its mainspring and its moving forces we are hardly more perfectly informed than were our barbarous ancestors of the days of the Greek and Roman civilization, or even of the time of Homer and the prehistoric ages. From the point of view of the mechanician, this machine—marvellous as it is as a study in anatomy, or to the investigator in physiology, in psychology, or in physics and chemistry—is strange and crude. It has not a revolving wheel or shaft, a cam or a gear, a belt or a piston, or a rigid system of mechanical "pairing," in the whole complicated and wonderful construction. Its operations, so far as mechanical, are all carried on by systems of levers, jointed in curious ways, and worked by cords of elastic muscle. Its mechanical operations and movements are all simple and easily traced and understood; but the forces and energies transferred and transformed are as mysterious in nature and method of action as their resultant effects in producing motion are simple. Some force—no one knows precisely what—and some energy, equally unidentified, cause contraction and relaxation of muscles and transformation of the unknown form of energy into mechanical power and muscular force and work. Where this energy of primary form is originated, what is its course, and how it affects the muscle, no one can say. Whether produced by chemical action in the assimilative organs, at which limit we lose sight of the material fed into the machine as the storehouse of the potential energy ultimately thus applied, whether given form in the capillaries and the lungs, where it

flows as venous blood and is transformed into arterial; whether created in some special organ of the system, in gland or nerve, or spine and brain, or whether arising through transformation in the muscle itself at the instant it is required for its work, no one can yet positively say. No man can assert that this energy is thermal, electrical, chemical, physical, or whether it is some as yet unfamiliar and, to the biologist, novel and peculiar form of energy which has escaped the hands and eluded the view of the man of science, learned in chemistry and physics and in all the transformations of exterior energetics.

What we do know of the complicated and puzzling sphinx is this.

Oxidizable substances, always vegetable in origin directly, as the fruits and grains, or indirectly, as the flesh-foods, are taken into the furnace, as some suppose, into the alembic, or whatever the stomach may be considered, and are there subjected to a chemical process of solution, with chemical transformation into compounds capable of absorption by the fluids of the system. They are then, with suitable further treatment, such as the emulsification of the fatty matters, taken into the circulation, and become a part of the blood. Continuous circulation between the heart and the various organs of the body and through the capillary system, and into and out of the lungs, alternately charges this vital fluid with deoxidized and carbonized substances and oxidizes them, throwing off the resultant carbon-dioxide, carbonic acid as it is more familiarly called, into the surrounding atmosphere. It is known that only a fraction, in rare cases not one-fourth, of all the food supplied is utilized to the extent of absorption into the circulation. It is now perfectly well known what is the nature and the quantity of the chemical compounds rejected by the animal machine in its working condition, as well as what are the constituents of the always combustible materials furnished it; but no one yet knows just how these materials, as reconstructed and absorbed into the circulating fluid, are made to produce energy, or what the energy unquestionably produced in large quantities, which are approximately measurable, is like, or how that or any other energy that may also exist in the system is stored, transferred from point to point, or transformed and utilized as mechanical or other power. At the end of the nineteenth century it is not yet ascertained whether heat, electricity, a vital

energy of as yet undetermined character and method of operation, nerve and brain power, mental force as a distinct energy, or what other, if there be any other, energies are the intermediary between the potential energy of the food and the applied energy of muscle, nerve, brain, chemical forces of digestion and nutrition, automatic powers of vitality, and mental and bodily action. With the entrance of the prepared nutriment into the system, all traces and clues of the mystery are lost, and the most learned man of to-day is as ignorant of the nature and action of the vital and other processes that preserve, repair, and operate this most intricate and curious of machines as the most ignorant savage. We can eliminate some current hypotheses, and to that extent approach the real source of life and action, and may possibly obtain some hint of the nature of these concealed forces; but the problem remains still one of the most attractive, tantalizing, and important of all the unsolved mysteries of science.

We know that peptonized and otherwise prepared food, always of vegetable origin and in oxidizable form, in that sense combustible, passes into the vital machine, and that a large fraction is rejected unutilized, together with considerable volumes of products of combustion leaving by way of the lungs, as exhalations of unknown amount by way of the skin. Large quantities of energy, in the form of heat, are carried out of the system and conducted and radiated from the skin. All the work of the muscles, whether performed upon external objects, in the movements of the body, as in walking and in the labor of the hands, or applied to the automatic processes which are essential to life, as digestion, circulation, and breathing, or to those which simply characterize animal life, as perception, observation, and thought, is also rejected energy. No energy is, or can be, destroyed in the vital or any other system, and all that enters is balanced by a corresponding quantity leaving it. Probably substantially all the internal, automatic work of the living machine is performed in respiration and the circulation of the fluids of the body through their miles of narrow channel and capillary ducts. This is work of friction, and all of it must be reconverted into heat; it constitutes a large part, if not the whole,* of the heat thrown out of the system.

The lungs reject compounds familiar in common life as pro-

* Rubner confirms this anticipation by his experimental researches.

ducts of combustion. But the temperature of the animal system is necessarily lower than the boiling-point of water throughout, and usually less than 100 degrees Fahrenheit, often falling to nearly the atmospheric temperature, or, in the case of fishes, to that of the water in which they live. This combustion or oxidation must take place at a temperature thus limited, and must consequently be an entirely different process from that familiar to us in the furnaces of the "heat-engines." It is more like that seen in the rusting of iron, the decay of wood or the processes of the chemist's laboratory. But, curiously enough, the breaking up of organic substances by the processes of non-vital natural decay is known to result largely, if not mainly, from the action of microbic parasites, and this fact is one of the evidences against the once usual theory that the animal machine is a heat-engine and its thermal product that of its furnace. That chemical affinities originate all energies of the vital system is undoubted; but all intermediate steps between the introduction of its potential energy into the body and the development of the transformed equivalent in dynamic and thermal energy are as yet concealed from us.

The question whether the animal machine is a heat-engine characterized by singularly low-temperature combustion, as formerly assumed, is promptly settled, and beyond dispute, by the fact that the whole system is of substantially uniform temperature. In all known heat-engines, the conversion of thermal into mechanical energy is consequent upon variations of pressure and volume of working fluids within a range of temperature, the extent of which limits the proportion of heat which may be thus utilized. The narrower this range, the less is the work performed and the smaller the proportion of the heat supplied which is transformable into dynamic energy and work. In the best modern steam-engines, this range is, at best, not above one-fourth the whole scale measured from the temperature of the steam down to the absolute zero at which all heat-motion ceases, and only this proportion could be utilized, at best, in a perfect machine. The proportion is higher in gas engines; but the wastes are more than proportionally greater in the engine as actually operated, and the two forms of heat-engine are practically to-day about equal. In the animal machine this range is very nearly zero; all parts of the fluid mass and contained solids

being, in the human body for example, held at about ninety-eight degrees Fahrenheit. The animal machine therefore cannot produce thermo-dynamic transformations, unless by some as yet undiscovered process which entirely evades the well-established laws of thermo-dynamics as applied to the heat-engines familiar to us. To produce such effects it will be necessary to carry parts of the system through a range of temperature equal to that of the steam-engine, if the known efficiency of the machine is to be secured in that manner. This is obviously an impossibility.

The deduction follows that the animal machine is not a heat-motor, or a thermo-dynamic engine; which deduction may be accepted as very nearly, if not absolutely, certain. The consequent conclusion thus follows that it is an engine operated thermo-electrically or by some other less familiar, very possibly entirely unknown, process of energy-transformation.

Many distinguished men of science have been attracted by these riddles of the vital machine, and have tried to read its oracles; but with little success as yet. Joule, as early as 1843, called attention to the fact that the machine must be one for transformation of energy, and found that the result should be a lower proportional development of heat, for a given volume of product of oxidation exhaled, when at work than when at rest. This conclusion was experimentally confirmed by Hirn, in 1858, by actually confining men and and women and youth in hermetically sealed chambers, into and out of which air could be introduced, and the contaminated atmosphere discharged, only through ducts so arranged that he might readily and accurately measure their volume and analytically determine their constituents. He found that the heat, the work, the volume of carbonized gases, had those general relations of quantity which had been predicted by Joule as a consequence of the then newly accepted laws of energy-transformation. The larger the amount of energy applied to external work, the less the quantity of energy rejected in other forms. The human machine and motor obeys the laws of energy as precisely as does the steam or the gas engine; although this fact is not a proof that it is a heat-engine, but simply indicates that it is a transformer of energy by processes the nature of which we have not yet ascertained. Similarly, the dynamo-electric machine in this sense complies with the laws of energetics

and yet is unrestricted by any law limiting its efficiency such as fetters the heat-engines.

Messrs. Becquerel and Breschet and later investigators have found, by actually introducing slender, needle-like thermometers into the flesh, that the temperature of the body is substantially the same in all parts. The muscles are one or two degrees higher in temperature than the skin tissue, and, during exercise, they may rise a degree or two higher still; but there is no point in the body, so far as can be ascertained, at which the heat exceeds the mean to any important extent. Hirn and others have shown that the human machine has at least the efficiency of the best steam engines; that is to say, it converts as large a proportion of its supply of energy into work as the best heat-engines. This would, were it a heat-engine, a thermo-dynamic machine of similar character, compel the provision of steam-boiler temperatures within the body—a simple impossibility in a mass composed mainly of fluids evaporating at the boiling-point under atmospheric pressure and of tissues altered by temperatures not greatly in excess of that standard. Experiment also shows the arterial blood to be but two or three degrees, at most, above the temperature of the venous; cold-blooded animals, as the fishes, usually exhibit no greater excess of heat over the fluid in which they live, and the molluscs practically coincide in temperature with the water about them. Exercise, increasing the temperature of all living mechanisms, notwithstanding the increased amount of energy drawn from the store and converted into work, raises the temperature of the whole machine and causes large increase in the quantity of heat conducted, radiated, and exhaled; but this very possibly comes mainly of the increased heart action, accelerating the flow of the currents in the arteries and veins and the conversion of its friction-work into heat. The fact gives no clue to the secrets of the vital sphinx.

Galvani showed that the nerves could be traversed and the muscles contracted by a current of voltaic or of high-tension electricity, and many later investigators confirmed his statements, while still others have shown that currents actually traverse the muscular and nerve tissues which originate in the body, and which, reversing Galvani's experiment, reveal their nature by all the tests familiar to the physicist as detecting the presence and measuring the action of electric currents from artificial sources.

The potentialities of the animal machine are developed in this direction most strikingly in the gymnotus and many other creatures, in which the currents are produced in great power and intensity, and directed, at will, in the capture of their prey or in self-defence, sometimes disabling a man or felling an ox by their powerful discharges. The fact of the transformation of energy is well illustrated in these cases by the exhaustion of the creature when it has continued this discharge of electrical energy a short time. To this extent, certainly, these animals are electro-dynamic machines. The electric eel and the torpedo are but the two best known of about fifty such electro-dynamic animal machines already discovered, and it is thought by some authorities that all animals possess this power of producing and applying electric energy in less degree. Faraday found that the gymnotus, the electric eel, has a storage power equal to that of fifteen large Leyden jars. It is probably well-established that every muscle and nerve of every animal is traversed by energy closely related to the electric current, and Daguin calls this "*l' électricité vitale.*"

Perhaps the most beautiful and striking of all the potentialities of the animal machine is that exhibited by those in which energy, whatever its nature, developed and stored in the body, or applied in its various curious and intricate operations, is made to take the form of light. In all the practical work of the engineer and of the man of science, light is only obtainable by the production of high temperatures, and the brighter the light the higher must be the temperature of its source. At 700 degrees to 800 degrees Fahrenheit a red glow only appears; at 1,000 degrees almost white light is produced; at 1,500 degrees to 2,000 degrees the radiance becomes brilliant, and the dazzling lights of the electric arc and of the sun indicate temperatures measured by thousands of degrees. Yet, on the other hand, we find light produced in nature without perceptible heat. Moonlight is sunlight almost freed from heat; its warmth is not only insensible, but so feeble that it is only by Professor Langley's famous "bolometer," an instrument of unimaginable delicacy, that science can measure it at all. The phosphorescence of the decaying stump or fallen tree in the forest, and that of the animalculæ with which the waters of tropical seas so frequently teem, are examples of the production of light without heat, and, in the case of the latter at

all events, at very nearly the temperature of the animal organism and of the surrounding sea.

The glow-worm and the firefly are provided with apparatus especially designed by nature for the production of this low-temperature light, free from heat, and Professor Langley and his colleague, Mr. Very, have shown by bolometric tests that this light from the animal machine is comparable only with moonlight in its freedom from heat. In other and, for our present purposes, much more significant, words, the vital machine converts energy into pure light without wasting it in the form of heat. In the familiar forms of artificial light, the heat, which is not only wasted and thrown away, but is a source of great annoyance and a real evil in many ways, constitutes an enormous proportion, often ninety-nine per cent., of the energy expended, and a proportional part of its cost is thus thrown away with it. We pay one or five per cent. of our bills for the light received, the balance for the heat wasted; very much as, in the heat-engines, we pay often a similar proportion for power received and a balance of equal proportionate amount for the heat thrown away unutilized; one or five cents in every dollar paying for value received, ninety-five or ninety-nine cents being paid for wasted, yet no less costly, energy. Gas and bright oil-flames, electric glow and arc lamps, respectively, return us one, two, and ten per cent. of the energy transmitted to them for transformation into light; while the moon and the glow-worm or firefly give us light without sensible heat. The animal as a light-producing machine is thus many times more efficient than the apparatus of the electrical engineer; it seems possible that we may find this vital mechanism but little less economical as a motive machine, and serving as a guide to the construction of artificial apparatus that shall displace the heat-engines and utilize the enormous proportion of their energy-supply now wasted.

Scientific investigation, on the other hand, has discovered facts which decidedly conflict with our theories of thermo-electric and electro-dynamic transformations of energies in the vital machine. The velocity of the nerve impulses is but about 90 feet per second in cold-blooded, and two to three times that speed in warm-blooded, animals; while electric currents are ordinarily inconceivably more rapid; thus indicating peculiar conditions of electrical conduction, if this be the mode of communication along

the nerve, or, perhaps more probably, something like a mechanical or a wave-like transmission, molecule acting by contact with molecule, as often observed in muscular movements. The originating form of energy and method of energy-conversion in the brain and spinal cord remain, in any event, as obscure as ever. It is found, also, that light and heat may be produced, and sometimes are produced, by the combustion in the animal system of certain fatty fuels capable of oxidation at these low temperatures, with liberation of heat and light at the same low intensity, thus safely burning without danger to the tissues. The probability that this may be a customary method of production of heat in the animal machine is thus indicated, and the mystery in such case is that of nature's method of producing such fuels from foods and of conducting their combustion.

Summarizing the argument : the animal machine, the vital prime motor in which we live, is supplied daily with an amount of energy in its food equivalent, dynamically, to the potential energy of a pound of coal. This is, in turn, the equivalent of one-fifth of a horse-power for twenty-four hours. A day's work is at most one-eighth of a horse-power for one-third of a day, at steady labor, one twenty-fourth as an average for the twenty-four hours. Thus measured by the labor of a working man, the animal machine utilizes one-fifth of the energy supplied it, just the efficiency of the best steam engines that the greatest inventors and best mechanics of our time have been able to produce. But it does much more than this. The brain takes from one-fifth to one-tenth of the original stock of energy ; all the work of digestion, respiration, and circulation, and of every muscular movement, voluntary and involuntary, and all that of reconstructing and repairing tissue of muscle and nerve and bone, must be added, and the efficiency of this prime mover is thus very far in excess of twenty per cent. and of the performance of the best engines. The experiments of Hirn, showing the rejected heat-energy to be twice as great, proportionally to oxygen inhaled, when at rest as when at work, indicates the total efficiency to be about fifty per cent. or two and a half times as great as in the best engines of human construction ; the production of power being the gauge. Langley has shown that, where the animal machine produces light, it does so at a cost, substantially all heat being eliminated, of probably a small fraction of one per cent.

of that of our familiar lights; and other investigations show that, where adapted to the production of electricity of high tension, as in the gymnotus, it does this by consuming food—combustibles composed of the same elements, mainly, as our fuels—and, by this direct evolution, escapes the loss of nine-tenths or ninety-five hundredths of the energy drawn upon in our artificial methods of electric light and power generation. Heat production must be similarly economical in the animal machine; as there are no important losses from it, it produces just enough to keep its temperature normal and constant under its covering of non-conducting hair or wool. In all these vital operations, heat and power are always produced and observable. Indications of the generation and use of electricity or some similar energy are detected in all animal machines, and sometimes electricity, also, in large quantity and of high intensity. In some instances the production of light is a result of transformation of energy in these machines, and thus the animal system illustrates the transformation of energies in all known ways, exhibits direct transformations unknown in applied science and engineering, and excels always, and sometimes enormously, in the efficiency with which it effects these transformations and performs its special tasks.

Could the inventor, the man of science, the engineer, compete with nature in these directions, it is evident that the stores of fuel, now so rapidly wasting before the growing demands of civilized races, would last many times longer than now appears probable; the period when the race must bore into the interior of the earth or remove to the tropics to obtain heat and power would be proportionally delayed. A day's work or a dollar would become equal in value to a large multiple of the value to-day measured in heat, light, electricity, or mechanical power, and the human race would be enriched and advantaged inconceivably through the discoveries of science and the ingenuity of the inventor, the mechanic, the engineer. That such outcome of the labors of scientific men is certain, no one can say; that it is probable, no one will deny; that it is possible, every one will admit. The future undoubtedly will display more and greater wonders as the fruit of intelligent scientific investigation, than has the past, than has even the generation just past. Among these marvels, it is safe to predict, will come at least some approximation to nature's methods of production of all the energies.

Whatever may ultimately prove to be the facts of physical, chemical, dynamic, energy-conversion, by the physiological processes of the vital organism, it is unquestionable that their study is imperative; and the reading of the riddles of this living sphinx constitutes a standing challenge to the man of science and the engineer; for within these mysteries are hidden the secrets of mightier powers than have yet been, in the remotest degree, approximated by man. Once these economies are attained by the engineer, in artificial heat, light, and power production, he will have insured proportional increase in the life of the race and in the sum of human comfort and happiness, and will have led in the elevation of the whole social system to an inconceivably higher level.

R. H. Thurston.